

Observations of Polarization in the Cosmic Microwave Background: A Progress Report for the POLAR experiment

C. O'Dell^a, B. Keating^b, J. Gundersen^c, L. Piccirillo^d, S. Klawikowski^a, N. Stebor^c, P. Timbie^a

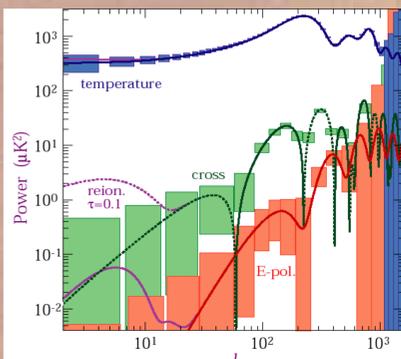
a. University of Wisconsin-Madison, b. California Institute of Technology, c. Princeton University, d. University of Wales-Cardiff, e. University of California at Santa Barbara

Why Measure CMB Polarization?

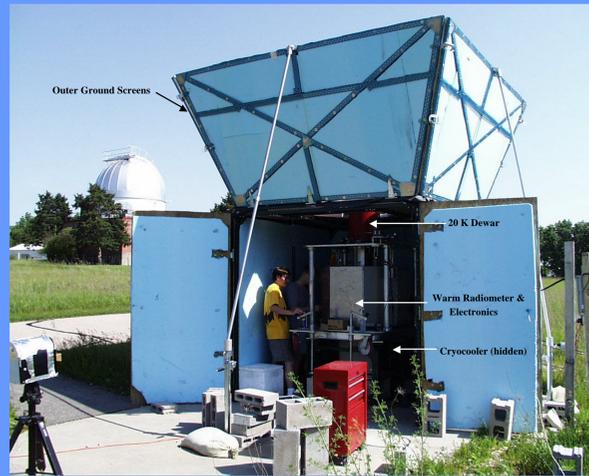
In 1965, measurements of the temperature of the Cosmic Microwave Background (CMB) helped verify the Big Bang Model of Cosmology. Recently, accurate measurements of CMB anisotropy have shown that we live in a geometrically flat universe, and have provided more evidence for inflation. There is, however, a third property of the CMB that can yield even more cosmological secrets: its polarization.

The CMB is theorized to be polarized an amount less than or equal to 10% of its anisotropy level. This level depends sensitively on both the reionization history of the universe, and on angular scale, as well as all the cosmological parameters. In general, we need several numbers to characterize CMB polarization, not just one. In terms of power spectra, there are E-mode, B-mode, and TE cross-correlation power spectra. E-mode power spectra result from density perturbations in the early universe, while B-mode power spectra are generally caused by gravitational waves. In addition, "E" is expected to be correlated with temperature anisotropy at a level of 10-30%, yielding the "TE" mode. E and B are related to the linear Stokes' parameters Q and U by $E(B) = Q(\bar{n}) + (-) iU(\bar{n})$.

The POLAR (Polarization Observations of Large Angular Regions) experiment measures CMB polarization at large scales, and will primarily be able to constrain the epoch of reionization of the universe. POLAR measures both Q and U, and thus will place independent constraints on large-scale E and B power spectra. In addition, POLAR will be sensitive to galactic synchrotron radiation, whose polarization properties have not been measured at frequencies above 1.4 GHz.



Theoretical Power Spectra of CMB Polarization, E and TE cross-correlation. Temperature anisotropy is shown to give the viewer some perspective. E-pol is shown both with and without reionization. Note the "reionization peak" at low multipoles for the case of $\tau = 0.1$. Error bars are those expected for the MAP satellite. (figure courtesy Wayne Hu)



POLAR Radiometer Specifications	
Receiver Temperature	35 K
Amplifiers	NRAO 26-36 GHz HEMTs (1st stage InP)
NET	~ 1 mK √ Hzsec
Channels	Five: 2 Polarizations (Total Power), 3 Correlation (26-29 GHz, 29-32 GHz, 32-36 GHz)
Bandwidth	~ 7 GHz
Beam Specifications	7°, sidelobes < -40 dB
Scan Strategy	Zenith Drift Scan at declination 43.1° (36 7° pixels)

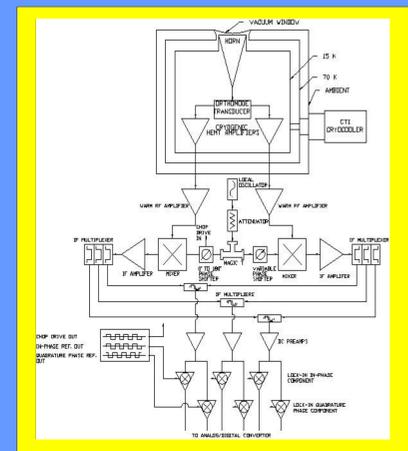


POLAR: A large-scale view of the instrument is shown above. A cryocooler cools the dewar to ~ 20K, inside of which lies our 30 GHz radiometer. The warm IF section of the radiometer as well as control electronics lies below the dewar. The entire apparatus spins at ~ 2 rpm. Polarized signals will show up as sinusoids with frequency = twice the rotation frequency; this allows synchronous detection of Q and U and is, incidentally, how POLAR "chops". Both the warm radiometer and the POLAR "cube" are temperature controlled to ensure signal stability.

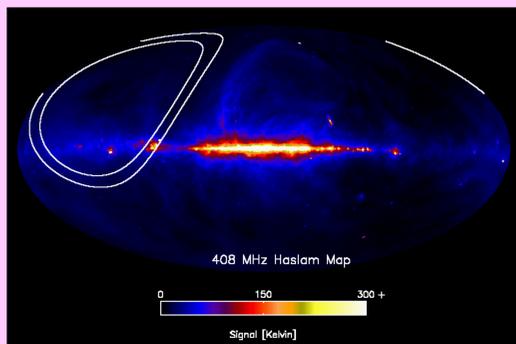
There is both an inner co-rotating ground-screen and a fixed four-panel outer ground screen in order to reject terrestrial signals. A 7° FWHM conical corrugated feedhorn is used in the front end. The observing site is located in Pine Bluff, WI at a latitude of 43°. POLAR performs a simple zenith drift scan and maps out a ring about the NCP, and obtains ~ 36 pixels.

The Signal Chain:

- Signal enters feedhorn from above
- Signal split into "x" and "y" polarizations with wide-band Orthomode Transducer.
- Signals pass through isolators, then HEMT amplifiers (~ 25 dB gain), then out of the dewar to warm radiometer.
- Signals amplified with warm RF amplifiers.
- Signals downconverted to IF frequencies (2-12 GHz) with 38 GHz Local Oscillator; one arm is phase modulated at ~ 1000 Hz to allow lock-in.
- Signals amplified again
- Signals each split with power divider; Total Power signals detected.
- The remaining signals are amplified again to ~ +10 dBm of power, then multiplexed to our three sub-bands.
- Each sub-band signal is run through a phase corrector, then the x- and y-polarizations are multiplied in a double-balanced mixers. All signals are then pre-amplified, low-pass filtered at 5 Hz, and run through a lock-in-amplifier. The signals are sent through a 16-channel DAQPad™, and recorded to a portable laptop computer.



Scan Strategy

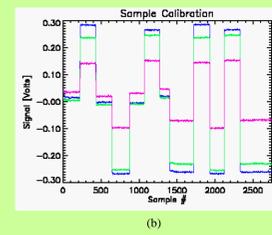
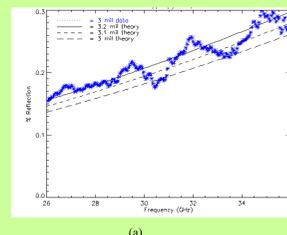
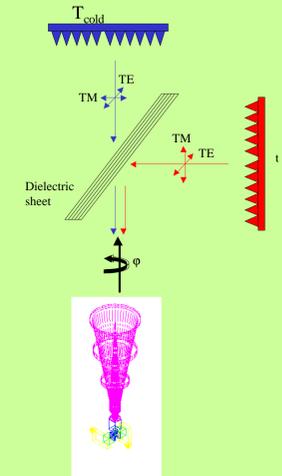


The figure above shows POLAR's scan strategy overlaid on a galactic map of synchrotron radiation at 408 MHz. The ring at declination 43° resulting from the zenith drift scan yields ~ 36 7° pixels. We pass through the galactic plane twice. Extrapolation of the low-frequency synchrotron maps to our frequency band of 26-36 GHz suggests that galactic synchrotron will dominate our signal. The total power signal can reach as high as 4-5 mK, and is perhaps 50 μK at high galactic latitudes. Synchrotron radiation can be up to 75% polarized, but typical values are truly unknown at these frequencies. A measurement of polarized galactic synchrotron by POLAR would contribute greatly to our understanding of galactic synchrotron, and the level at which it will affect future CMB polarization missions.

Calibration

Calibrating a polarimeter is not quite as simple as for a total power radiometer. This is because one must determine the Volts/Polarized Kelvins of the instrument. Ideally, this would be done under conditions as similar as possible to the actual observing conditions; that is, inject a signal similar to the atmosphere in power but slightly polarized. Wire grids have long been used for this purpose, but have the drawback that they yield a 100% polarized signal. It is well known that thin dielectric films can polarize light scattered at oblique angles.

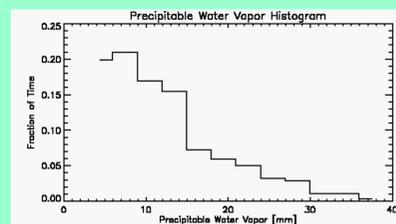
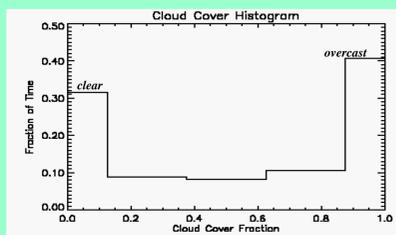
In order to calibrate POLAR, we simple replaced the wire grid with a thin (3 mil) polypropylene film. It can be shown that this yields a polarization signal of $T_{pol} = (T_{hot} - T_{cold})(R_{TE} - R_{TM}) \sin(2\phi)$ where ϕ is the rotation angle of the grid about the z-axis. For a 3-mil polypropylene sheet, theoretical calculations show that $R_{TE} \sim 0.2\%$ and $R_{TM} \sim 0.015\%$ at ~ 30 GHz. We verified these numbers experimentally (see fig (a) below). For $T_{hot} = 300$ K and $T_{cold} = 15$ K, you get a beautiful 0.185% polarized signal of ~ 530 mK. Plot (b) below shows a sample calibration, which evidences a high S/N for all 3 correlation channels.



Weather Conditions at Pine Bluff, WI during the Spring 2000 Campaign

The atmosphere is not believed to be polarized. Calculations at our frequencies show that atmospheric polarization levels should be less than 10⁻⁸ K. However, POLAR is highly sensitive to two aspects of the weather. First, because there is a small instrumental cross-talk between the total power and correlator channels, coupled with the non-uniform temperature distribution across a cloud, POLAR sometimes sees clouds in polarization. Second, water vapor in the atmosphere contributes to atmosphere temperature and 1/f noise. High water vapor contents often lead to data that is too contaminated to use.

Figures (a) and (b) show histograms of both of these properties during the POLAR Spring 2000 observing campaign. From the cloud cover plot, we see that most days were either clear or overcast (and on those overcast days it was often raining). Precipitable water vapor varied quite bit, from 3-4 mm on exceptional days, to upwards of 40 mm on extremely wet days. We keep only data with 10 mm or less water vapor, which cuts a substantial fraction of the data.



Performance and Results

POLAR performed well during its first season. The figure to the right shows a sample power spectrum for all 5 channels taken during clear weather. As you can see, the total power channels are dominated by 1/f noise to ~ 1 Hz, but the correlator channels are virtually free of 1/f noise. The 5 Hz low-pass filters are also very apparent. Polarized signals will show up at twice the rotation frequency of the instrument, labelled 2φ in the figure. The table below shows some of the details of the observing campaign.

Spring 2000 Observation Details	
Period of Observations	March 11 - May 29, 2000
Amount of Data Collected	750 Hours
Amount of Data during dry, clear weather	~ 90 - 150 Hours
Expected Sensitivity Limit (per Stokes' parameter)	10 μK/pixel (90% confidence)

This figure shows ~ 110 hours of our best data co-added on the sky in a least-squares way. We don't quite span all 24 hours of right ascension, but rather about 17 hours; this is because we cut all data when the sun was above 30° elevation. For the 34 GHz channel, there was essentially no instrumental offset, but for the other 2 lower frequency channels, there was a substantial offset in both Q and U; we are currently working on ways to remove these offsets while simultaneously minimizing its effect on the extracted signal.

However, the figure to the right is very encouraging. The data are oversampled to 100 RA bins of 3.6° width. Notice the conspicuous absence of the galaxy at ~ 5 hrs and 21 hrs. This will help set a stringent limit on the polarization level of synchrotron on large angular scales.

